An interconnection method for ultra-compliant electrodes.

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Abstract

We are developing a novel interconnection method to form reliable joints between truly stretchable electrode mounts and rigid substrates. This is needed as the electrodes must be connected to implanted electronics if they are to be used for long term implantation, and the components are most often mounted on a rigid substrate and protected within a solid enclosure. In this paper we describe the concept and report on preliminary results. Eight test samples were prepared, four of which started the underwater test. Their initial impedance ranged from 107 to 413 Ω and remained constant (standard deviation 6 Ω) for over two months submersion.

Keywords: flexible electrode, functional electrical stimulation, long-term implantation.

Introduction

Flexible, stretchable, electrodes are being developed by several research centres [1, 2]. They offer advantages over stiffer mounts, such as their ability to conform to the movements of the host, or to lower post insertion oedema pressure with cuffs. This is especially relevant in applications subject to frequent flexions and rotations (e.g. spinal electrodes for rats). True stretchability with wires can only be achieved if they are coiled or sinuous. This may be too space consuming in applications where miniaturisation is often critical. Hence, most new designs avoid the use of wires altogether, and instead include a flexible "ribbon" to channel the signal from the electrodes.

In use, the electrodes must be joined to a rigid substrate (carrying the electronics). This connection (sometimes referred to as "interconnect"), however, remains a challenge. In the absence of a wire, the joint can no longer be achieved via standard methods such as soldering. When the ribbon offers a firm interface, such as with Pt foil, it is common practice to use micro-rivets or possibly micro-welding [3]. However, this is not acceptable for truly stretchable devices, whose applications in FES would undoubtedly be numerous if only a new joining method, reliable for long-term implantation, was established.

In this paper, we describe a solution, based on a plasma bond between the stretchable PDMS mount and a glass layer on the rigid substrate. We also review results from preliminary underwater tests.

Material and methods

Concept

Truly stretchable electrodes can be produced by depositing a 5 nm chromium layer followed by a 25 nm thin film of gold over a PDMS membrane and patterning the metals [1]. A second PDMS layer, modified so as to be photo-patternable [4], may be spun over the first, leaving, after UV exposure and development, only the electrode sites exposed.

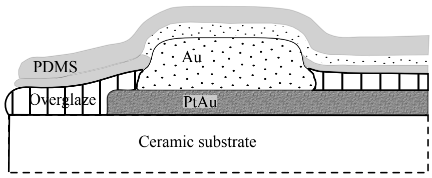


Figure 1: Concept: a sketch of a cross-section through the joint.

In our method, the connection pads on the ceramic are gold domes, surrounded by an insulating overglaze, but protruding over its surface. The surfaces of both parts, the rigid substrate and flexible electrode mount, are activated by exposure to an oxygen plasma. When the PDMS is laid (pad openings face down) over the overglaze, a long-lasting bond may be achieved [5]. As illustrated in figure 1, the PDMS is stretched over the protruding bump and the elastic tension maintains a close contact between the thick and thin-film gold, forming a reliable, metal to metal connection, provided the creep of the PDMS over time is limited. The quality of the plasma bond is critical, especially around the pads where it guarantees electrical insulation. For strain relief, the assembled connector may be further encapsulated in PDMS.

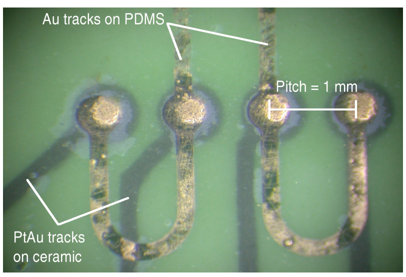


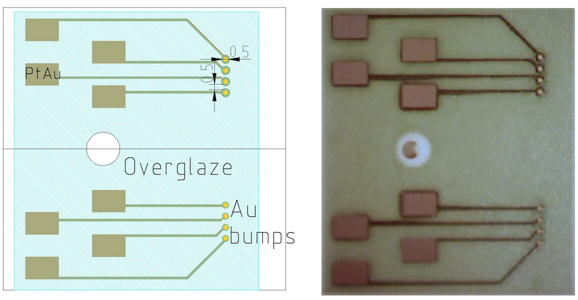
Figure 2: A test sample: a ceramic substrate with bonded stretchable PDMS test tracks.

Table 1: Printing sequence (with paste and firing temperature) of 3 or 4 layers on the three sets of substrates (A-C).

	A	**B**	**C**
1	Pt-Au ESL 5837 - 850 °C	Pt-Au ESL 5837 - 850 °C	Pt-Au ESL 5837 - 850 °C
2	Au ESL 8844-G - 850 °C	Au ESL 8844-G - 850 °C	Au ESL 8844-G - 850 °C
3	Overglaze ESL 4771-P1 - 525 °C	Overglaze ESL 4771-P1 - 525 °C	Au ESL 8844-G - 850 °C
4	Au ESL 8835 - 520 °C	–	Overglaze ESL G-485-1 - 600 °C

Sample preparation

Figure 2 shows an assembled test sample. The rigid substrate is a 1 inch square piece of ceramic (96 % alumina) with gold bumps, along with PtAu tracks and solder pads for wire connection and an insulating overglaze layer. The stretchable part is made of a thin-film gold layer on a 0.8 mm PDMS strip, as previously described in the concept section, but without the second PDMS layer [1]. The pads on the PDMS test pieces are linked, in pairs, by short U-shaped tracks (see fig. 2).
On the ceramic substrates, (fig. 3), the gold bumps are 0.5 mm in diameter. Four pairs are printed on a single substrate, grouped in two sets of two pairs each. The pitch of the bumps (and corresponding pads on the PDMS) within each set is 1 mm. The gold bumps are created by layering conductive inks: a first disk of PtAu is covered by one or two layers of Au forming pads of narrower diameters. To compare the effect of the dome height and shape, and the uniformity of the overglaze layer, we looked at three different layer stacks (table 1) and two patterns, with a PtAu disk diameter of either 800 or 600 μm. The overlaying gold pads all have the same diameter (450 μm for the first layer and 400 μm for the optional second layer). The opening in the overglaze, which defines the overall pad dimensions, has a diameter of 500 μm in all cases.



(a) Schematic of the ceramic substrate
(b) Photo of the ceramic substrate

Figure 3: Schematic drawing and picture of the ceramic substrate.

The ceramic substrates were prepared following standard thick-film printing methods. All pastes were allowed to level at room temperature after printing, for 5-30 minutes, before drying at 125 °C. The substrates were then fired in a belt furnace. The peak temperature was as recommended by the manufacturer, and sustained for 10 minutes for all layers. Both drying and firing were performed in air. The firing profile was slow enough, and air circulation sufficient, to ensure a careful burnout and elimination of the volatile components from the paste. Three sets of substrates were prepared (A, B and C), as detailed in table 1. The screens used were all fitted with 325 45° stainless steal mesh. The emulsion thickness was 20 μm for the Pt-Au, 30 μm for the Au and 10 μm for the overglaze. The overglaze was printed twice without levelling or drying delays, to obtain a "double wet print". The overglaze thickness after firing is around 10 μm. Typical profiles for each group are shown in figure 5.

Plasma bonding

Preliminary tests showed the need to re-glaze the substrates to minimise surface roughness and improve the plasma bond quality. All substrates were therefore fired a second time, in a belt furnace in air. The firing profile was faster than for the original firing step (an hour altogether). The time at peak temperature (750 °C) was 10 minutes.
To form a sample, a substrate and PDMS test piece were exposed to the oxygen plasma (nominal parameters: 29 W, 350 mTorr) for 2.5 minutes. Immediately upon venting, the PDMS was placed, exposed face down, on the ceramic. A few drops of methanol acted as a surfactant so the pieces could be slid into alignment (by eye, no magnification). The methanol was allowed to evaporate at room temperature for a few minutes before transferring onto a hotplate (100 °C). A wipe was placed on top of the PDMS to prevent sticking, followed by a glass slide and a 800 g weight. The sample thus compressed was baked for 1 hour.

Underwater impedance test

After soldering wires on the PtAu pads, the samples were cleaned and the solder pads coated with DC3140 to provide electrical insulation.
The samples under test are submerged in saline at 37 ℃, see figure 4. They are tested every 10 minutes, by biasing each pair of wires with a constant 2 mA current for 1 second. Just before the current is interrupted, the voltage across the pair is measured and stored for later analysis. The maximum bias voltage is 1.4 V to limit the risks of electrolysis in case of open circuit. The samples are also regularly connected to a spectrum analyser to monitor their non DC impedance.

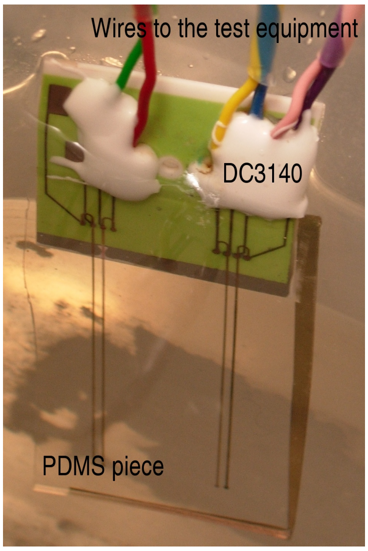


Figure 4: Test sample in saline bath.

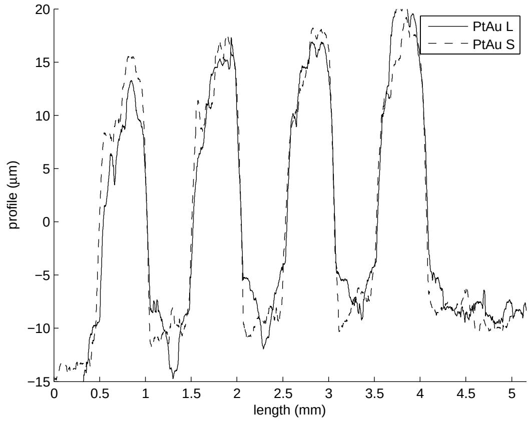
Results

Thick-film profiles

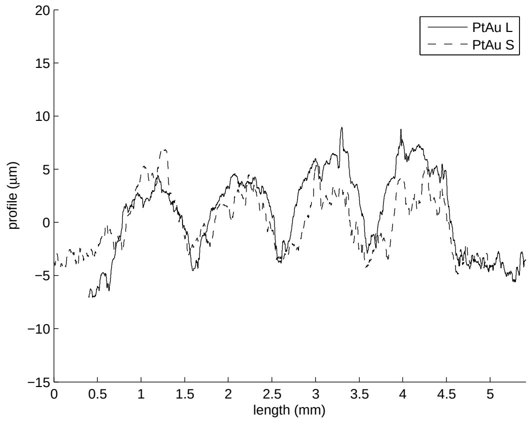
The profiles (measured before the re-glazing step) for all three groups and for both PtAu pad diameters, are shown in figure 5. Printing a second layer of Au after printing the overglaze gives noticeably taller bumps (comparing fig. 5(a) with fig. 5(c)). The effect of the larger PtAu disk is a widening of the base of the bump, up to a height of 5 to 10 μm. The bumps with a single Au layer were deemed too low and substrates from group B excluded from the bonding tests.

Underwater connection impedance

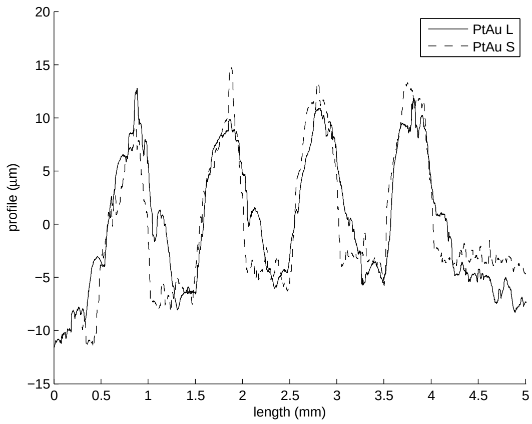
Four flexible PDMS pieces with four U-shaped tracks each were bonded on substrates of groups A and C, giving a total of 16 pairs. After bonding, the DC resistance of each pair was measured using a multimeter. All pairs with an impedance above 1 $k\Omega$ were labelled as failed bonds. The yield was 50 % and 8 pairs started the underwater test. Handling might have subsequently damaged 4 of them, as they displayed an intermittent connection failure. Hence we report here preliminary results on 4 bonded pairs.



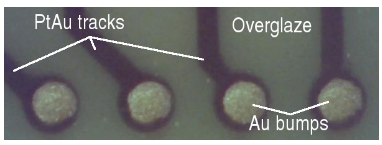
(a) Profiles for group A



(b) Profiles for group B

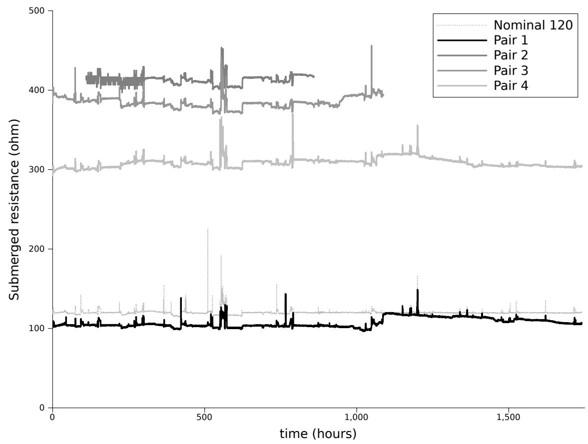


(c) Profiles for group C

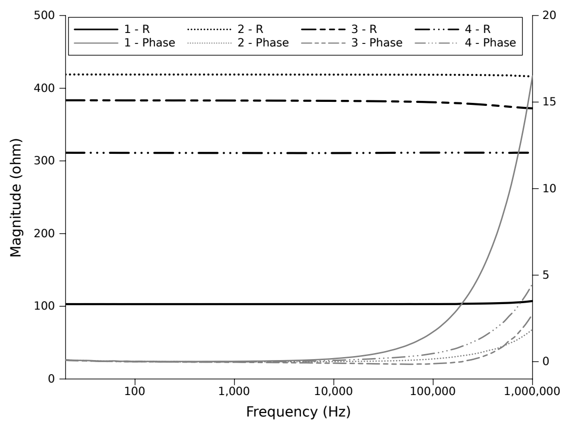


(d) Picture of the Au bumps (group C), with small (600 μm diameter) PtAu pads.

Figure 5: Profiles of gold bumps for each test group, for PtAu pads diameters 800 μm (L) and 600 μm (S).



(a) DC resistance.



(b) Spectra at 45 days (36 for the 413 Ω).

Figure 6: Evolution of the impedance of the tests pairs in saline at 37 °C.

Two pairs were removed from the bath (at 36 and 45 days) to be included in a separate test. The impedances of all 4 pairs, while submerged, remained constant, as seen on figure 6(a). The reading and data logging equipment itself introduces some fluctuations. To assess its stability, two resistors were also connected to the box. The standard deviation for a nominal 120 Ω resistor was 3 Ω (readings also plotted on fig. 6(a)), and 6 Ω for a nominal 1.2 $k\Omega$ resistor (with the current decreased to 0.2 mA).

The spectra of figure 6(b) indicate that the connections are truly resistive. The trends at high-frequencies are due to the influence of the long cables from the water bath to the spectrum analyser.

Discussion

As seen on table 2, the impedance values range from 100 to 400 Ω. We are investigating the possible causes of this rather wide spread. The pair with the lowest resistance was made using a group A substrate, the group with higher bumps. Noticeably, the pair with the highest resistance is also from group A. We will improve the bonding process to achieve a higher yield and produce a sufficient number of test pieces to obtain statistically significant results.

In these static tests, the impedances remained constant, some for a submersion time of over 2 months. These results are very promising. We have now initiated cyclic loading tests, where we monitor a pair's impedance while dynamically stretching the PDMS.

Table 2: Average impedance of submerged test pairs.

	R Ω	**SD** Ω	**Immersion** Days	**Group**	**PtAu** μm
1	107	6	72	A	800
2	413	5	36	A	800
3	384	6	45	C	600
4	309	6	72	C	800

Conclusion

In these preliminary experiments, we have shown that it is possible to achieve good interconnections between a truly stretchable thin-film gold on PDMS structure and a rigid ceramic substrate. Improvements are needed, such as the development of a more reliable bonding process to increase the yield.

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